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Expected Residence Time Model

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I. Introduction

The Transportation Technology Department of Sandia National Laboratories develops analytical and computational tools for the U.S. Department of Energy to assess the radiological consequences and risks from the transportation of radioactive materials by all modes. When large quantities of materials are to be transported, movements may occur over an extended period of time in what is collectively referred as a "shipping campaign". Since the routes over which the shipments occur often remain the same, cumulative exposure to individuals inhabiting the population zones adjacent to the transport links must be estimated. However, individuals do not remain in the same residences throughout their lifetimes and, in fact, move quite often. To appropriately allocate exposures among populations over extended periods of time, perhaps years, requires a model that accounts for three population categories; 1) the original populations residing in the areas adjacent to the transport links, 2) individuals moving out and 3) individuals moving into residences in the designated areas. The model described here accounts for these conditions and will be incorporated as a user option in the RADTRAN computer code for transportation consequence and risk analysis (Reference 1). RADTRAN is a computer code for estimating the consequences and risks associated with the transport of radioactive materials.

II. Methodology

The most mathematically elegant model would be predicated on an analytical "double exponential", composed of terms describing positive exponential biological ingrowth and negative exponential decay, with the latter made up of terms describing both individuals moving away and mortality. However, the associated coefficients describing these sub-populations must be empirically derived and can restrictively lead to instances in which the model does not apply to specific populations. Therefore, we selected the simpler methodology developed here, which is an extension of previous work (Reference 2) that uses available census data and is applicable to a wide range of problems.

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As a prerequisite in presentation of the methodology, it is necessary to define the major variables:

P_0 = Initial population in designated area

P_{in} = Population moved into designated area

P_{out} = Population moved out of designated area

$P_{remaining}$ = Population remaining in designated area

P_{total} = Total exposed population in designated area

The key to solution is application of two initial conditions: 1) over the time periods of interest, population distributions within the relatively small areas being analyzed are modeled as remaining constant, and 2) all established residences are modeled as being occupied. The latter condition means that although individual households may leave an area, other households move in to occupy the vacated residences (100% occupancy). Thus, although individuals in the population P_{in} are distinct from the individuals of P_{out}, the population groups are approximately numerically equivalent in magnitude ($P_{in} \approx P_{out}$).

This simplified procedure allows determination of the total exposed population (P_{total}) strictly as a function of P_0. Further, the 100% occupancy condition slightly overestimates the actual population. As some households may move to another residence within the area and since housing-unit occupancy may not be 100%, the calculated total population size will also be an overestimate (unless localized rapid population growth has occurred). The methodology proceeds from determination of the original population P_0, through summation of all individual link/bandwidth populations comprising the complete route. Over the time interval of interest (the period of the shipping campaign) household populations P_{out} and P_{in} will move out of and into the sample space, respectively. The quantity of interest, the total exposed population P_{total}, consists of the original population P_0 plus P_{in}, comprising the population of individuals who moved into the sample space during the campaign (Figure 1: Equation 1). At the end of the shipping campaign, P_0 consists of the populations of households which remained ($P_{remaining}$) plus those which moved out of the sample space (P_{out}) (Reference Figure 1: Equation 2).

It is important to note that the procedure considers populations and that the mathematical constructions are predicated upon census data expressed in terms of "households", and as such may not be applied to individuals. The households are contextually integrated into populations, inclusive of several regional, property-utilization, and density subgroups. Although some of the data subsets are available (Reference Table 1) and may be incorporated into the model, only the aggregate of all households is considered here.

$$P_{total} = P_0 + P_{in} \quad (1)$$

$$P_0 = P_{out} + P_{remaining} \quad (2)$$

$$P_{total} = (P_{out} + P_{remaining}) + P_{in}$$

$$P_{in} \approx P_{out}$$

$$P_{total} = 2P_{out} + P_{remaining}$$

$$P_{out} = P_0 - P_{remaining}$$

$P_{remaining} = P_0 \times R_t$, where R_t = Fraction of households remaining in same residence in t years

$$P_{total} = 2(P_0 - P_{remaining}) + P_{remaining}$$

$$P_{total} = 2P_0 - P_{remaining}$$

$$P_{total} = 2P_0 - (P_0 \times R_t)$$

$$P_{total} = P_0(2-R_t) \quad (3)$$

Figure 1. Derivation of Mathematical Algorithm

The result is an expression specifying the total population (in terms of "households") residing in an area over time t years (Reference Figure 1: Equation 3). Significantly, only the original population and the average time of residence need to be known. With respect to the transportation of radioactive materials, the relationship allows an estimate of the total population exposed over the entire interval of a shipping campaign to be developed, strictly as a function of the initial population density and duration of the shipping campaign. The derivation of the remaining variable R_t is adapted from published census data analyses (Reference 2).

Curve-fit coefficients, shown in Table 1, were applied to empirically determine the fraction of households moving into an area S_t, and the fraction remaining in their current residences R_t.

S_t = Fraction of households which moved into current residence t years before survey

$$S_t = \exp-[a_1 b_1(1-\exp(-t/b_1))+a_2 t+a_3 b_3(\exp(t/b_3)-1)] \quad (4)$$

R_t = Fraction of households remaining in same residence t years from present

$$R_t = p_t/a_1+a_2+a_3, \text{ where } p_t = \text{Probability density function} \quad (5)$$

$$p_t = S_t\{a_1\exp(-t/b_1) + a_2 + a_3\exp(t/b_3)\} \quad (6)$$

Category	a_1 (y^{-1})	b_1 (y)	a_2 (y^{-1})	a_3 (y^{-1})	b_3 (y)
All Households	.1503 (.0261)	1.88 (0.60)	.0679 (0.0108)	.0015 (.0044)	13.3 (11.5)
Renters	.3271 (.0219)	3.45 (0.57)	.0989 (.0112)	.0000 (.0013)	13.3
Owners	.0285 (.0264)	1.88 (3.45)	.0518 (.0255)	.0077 (.0172)	21.3 (20.4)
Farms	.0124 (.0424)	1.88 (10.92)	.0441 (0.0136)	.0012 (.0054)	13.3 (17.1)
Urban	.1744 (.0260)	2.07 (0.69)	.0561 (.0332)	.0081 (.0222)	21.1 (24.5)
Rural	.0617 (.0151)	3.62 (2.87)	.0658 (.0219)	.0007 (.0076)	13.3 (40.2)
Northeast Region	.0829 (.0138)	3.53 (1.92)	.0440 (.0461)	.0087 (.0298)	23.0 (33.3)
Midwest Region	.1286 (.0234)	1.98 (0.69)	.0653 (.0107)	.0016 (.0044)	13.3 (11.0)
Southern Region	.1812 (.0271)	1.63 (0.44)	.0682 (.0139)	.0029 (.0078)	16.5 (16.0)
Western Region	.2029 (.0436)	1.74 (0.66)	.0832 (.0121)	.0008 (.0034)	10.3 (10.7)

Table 1. Curve-fit parameters and (±) asymptotic standard errors (Israeli and Nelson, 1992)

The following example illustrates derivation of an equation to calculate the total exposed population of "all houses" for a multi-year shipping campaign. Values listed within Table 1 are first used to develop an expression for R_t.

$$S_t = \exp-[a_1 b_1 (1-\exp(-t/b_1)) + a_2 t + a_3 b_3 (\exp(t/b_3)-1)] =$$

$$\exp-[(.1503)(1.88)(1-e^{-t/1.88}) + .0679t + (.0015)(13.3)(e^{t/13.3}-1)]$$

$$S_t = \exp-[.282564(1-e^{-t/1.88}) + .0679t + 0.01995(e^{t/13.3}-1)]$$

$$p_t = S_t(a_1\exp(-t/b_1) + a_2 + a_3\exp(t/b_3))$$

$$p_0 = S(t=0)(a_1\exp(-(t=0)/b_1) + a_2 + a_3\exp((t=0)/b_3)) = a_1 + a_2 + a_3$$

$$p_0 = (.1503 + .0679 + .0015)$$

$$p_0 = .2197$$

$$p_t = S_t(.1503e^{-t/1.88} + .0679 + .0015e^{t/13.3})$$

$$R(t) = p(t)/p(t=0) = S(t)(a_1\exp(-t/b_1) + a_2 + a_3\exp(t/b_3))/(a_1 + a_2 + a_3)$$

$$R_t = p_t/p_0 = S_t(.1503e^{-t/1.88} + .0679 + .0015e^{t/13.3})/(.2197)$$

$$R_t = \{\exp-[.282564(1-e^{-t/1.88}) + .0679t + 0.01995(e^{t/13.3}-1)]$$

$$* (.1503e^{-t/1.88} + .0679 + .0015e^{t/13.3})\}/(.2197) \qquad (7)$$

Figure 2. Derivation of R_t

Substituting the relation for R_t of Equation 7 into Equation 3 yields:

$$P_{total} = P_0[2-R_t] \qquad (3)$$

$$P_{total} = P_0(2-R_t) = P_0[2-\{1/(.2197)$$

$$* \exp-[.282564(1-e^{-t/1.88}) + .0679t + 0.01995(e^{t/13.3}-1)]$$

$$* (.1503e^{-t/1.88} + .0679 + .0015e^{t/13.3})\}$$

$$P_{total} = P_0$$

$$* [2-\{4.5516614\exp-[.282564(1-e^{-t/1.88}) + .0679t + 0.01995(e^{t/13.3}-1)]$$

$$* (.1503e^{-t/1.88} + .0679 + .0015e^{t/13.3}). \qquad (8)$$

In a recent environmental assessment of the impacts of transporting foreign research reactor spent nuclear fuels (Reference 3), a total population of approximately 139,403 persons was estimated to be exposed during highway transport along the route from Charleston, SC to the Savannah River Plant near Barnwell, SC. For a shipping campaign lasting 10.0 years, substitution of time t=10 years and initial population of P_0 = 139,403 persons into Equation 8 yields a total potentially exposed population P_{total} = 261,747 persons. Significantly, the total potentially exposed population (P_{total}) is nearly *twice* the initial population (P_0), formerly the only value used in dose-consequence analyses of shipping campaigns.

IV. Conclusions

A method has been developed for estimating the total potentially exposed population of persons residing near transportation links, during time intervals required to complete a shipping campaign based upon U.S. Bureau of Census data and analyses (Reference 2).

This method has several strengths including simplicity, dependence on few critical parameters, and a firm foundation in empirical data. Conversely, two weaknesses of the method are; 1) one cannot readily account for rapid changes in overall population density (examples being explosive population growth or decline resulting from abrupt socioeconomic changes brought about by extensive construction projects or military facility closures), and 2) it is not possible to account for less than 100% occupancy factors. However, in all cases but those associated with rapid growth, the method yields estimates that are slightly conservative (i.e. overestimates the total exposed population). Should a route segment experiencing rapid and significant growth be identified in a specific application, then additional calculations may be required to improve the population estimate for that link.

The ultimate consequences of application of this methodology are twofold. First, the calculated average dose to members of the public residing near transportation routes will decrease, as not all persons remain near a link for the full time period of the shipping campaign. Secondly, the statistical data presented in Table 1 are amenable to uncertainty analyses, which in turn yields improved dose-consequence estimates for the population group.

V. References

1. "RADTRAN User's Guide", K.S. Neuhauser and F.L. Kanipe, Sandia National Laboratories, Albuquerque, New Mexico, 1992.

2. "Distribution and Expected Time of Residence for U.S. Households", Miron Israeli [Israel: 011 972 8434 364] and Christopher B. Nelson [(202) 233-9209], Risk Analysis, Volume 12, No. 1, 1992.

3. "Environmental Assessment of Urgent-Relief Acceptance of Foreign Research Reactor Spent Nuclear Fuel", U.S. Department of Energy, Washington, D.C., April 1994.

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